basal diameter, judged from a distance of about 300 feet, was from 10 to 15 feet. Leaves and trash were included in the swirl for a height of not less than 5 or 10 feet, resulting in a dense blackish cloud to this height. Had the whirl been observed from above, its rotation would have appeared counterclockwise. When south of the observer the column still seemed to lie in the general direction of the sun, although probably mainly *ahead* of the position of the ground end.

The spiral died out on a rocky point about 500 feet south of the back corral at about 1.25 p. m., the upper part of the dust column floating for some time after the ground swirl had disappeared.

The wind about noon had been variable—northwest, north, northeast, and east. The northwest and east winds are less common here than those from other directions. At about 1:25 p.m., there was almost no wind on the station grounds. The day was clear and hot with a maximum shade temperature of 81° at 2 p. m., and 80° at the time of the phenomenon.

Section 21 is a cutover area with few trees now standing, and it is possible that the whirlwind originated there. The soil over this area is mainly residual from basaltic rock, is scantily covered with vegetation, and bakes badly when exposed to the sun, thus reflecting a large amount of heat.

KÖPPEN'S CLASSIFICATION OF CLIMATES: A REVIEW.

By PRESTON E. JAMES.

[Clark University, Worcester, Mass., March 15, 1922.]

One of the most important contributions to the subject of climatic regions is that of Dr. Wladimir Köppen, published in Germany in 1918.[1] This classification is revised and remodeled from an earlier one, proposed in 1901, and largely based on vegetation zones. In the revised scheme (see Fig. 1), the general plan of the vegetation zones may still be seen, but in determining his boundaries he now uses the decisive climatic criteria which are fundamental in the distribution of vegetation. Köppen includes in the diagrams accompanying his article a map of an ideal continent without relief (see Fig. 2). On this he places his climatic regions, drawn as they theoretically would lie if relief and irregularity of land and water were eliminated. An explanation of the departures from the ideal scheme in the several continents would make a profitable study for university students who have sufficient preparation.

This classification has not been made available in English for detailed use. It was reviewed by Professor Ward[2], who also reproduced Köppen's map in black and white. But a detailed statement of the criteria for the subdivisions is not available. It is this want, which the present reviewer hopes to fill.

GENERAL PRINCIPLES USED.

When we consider the distribution of climates in general over the earth, it may be seen that the regions of maximum human development lie between two desert regions—the deserts of ice, and the deserts of sand. In these deserts life is negligible, although the cold regions are far more hostile than the hot deserts, since in the latter every shower may awaken the germs of life, and man may encroach on their boundaries by the use or irrigation. But between them, broadly speaking, human development of a high order is confined. These regions, therefore, may be taken as the supports, so to speak, of the system. They merge into the "life zone" by transition types, the tundra and the steppe, respectively. In the deserts vegetation is lacking; in the transition types we find low bushes and grass; elsewhere trees grow to considerable heights.

The deserts of ice form a polar cap, drawing a limit beyond which there is no life; but the deserts of sand lie in two girdles about latitude 30° north and south, and are separated by a constantly rainy climate along the Equator. Furthermore, since these deserts lie in the trade-wind belts,[3] they are driest on the lee coasts, and are interrupted by more humid regions on the eastern, or windward, sides of the continents.

The regions not included in these two big types and their transition zones are divided as follows: (1) The winterless region, which lies between the deserts of sand along the Equator; (2) the warm temperate region; (3) the sub-Arctic region. Since the latter does not occur in the Southern Hemisphere, the term sub-Arctic is permissible.

These three regions are again subdivided on the basis of rainfall distribution, as in the following table:

1. Winterless region.
   (a) Constantly rainy climate.
   (b) Periodically dry climate.
2. Warm temperate region.
   (a) Dry season absent.
   (b) Dry season in winter.
   (c) Dry season in summer.
3. Sub-Arctic region.
   (a) Dry season absent.
   (b) Dry season in winter.

It can be seen that 1 and 3 are divided into only two regions each, while 2 is divided into three. In the Tropics the total variation of temperature is so slight that it is unimportant in what season the rain comes, so that it is sufficient to distinguish between a constantly rainy and a periodically dry climate. In the sub-Arctic region there is no example of a dry season in summer, so that the first two divisions of the warm temperate region may be used farther north also.

The combination of these types results in 11 climatic regions. These 11 regions are applied to the earth, and given the numbers as in the following table:

1. Tropical rainy forest climate.......	A. Tropical rainy climates.
2. Periodically dry savanna climate..	
3. Steppe climate..................	B. Dry climates.
4. Desert climate..................	
5. Warm climate with dry winters...	C. Warm, temperate rainy climates.
6. Warm climate with dry summers...	
7. Damp climate with mild winters..	
8. Damp climate with severe winters..	D. Sub-Arctic climates.
9. Cold climate with dry winters.....	
10. Tundra climates..................	E. Polar.
11. Perpetual frost climates..........	F. Climates.

[1] W. Köppen: Klassifikation der Klimate nach Temperatur, Niederschlag, und Jahreslauf. *Petermann's Mitteilungen*, September, October, and November-December, 1918, vol. 64, pp. 193-203, and 243-248, with map and diagrams.

[2] R. De C. Ward: A new Classification of Climates. *Geographical Review*, September 191 8, vol. 8, pp. 188 to 191, with map.

[3] This statement needs some modification. The deserts of the globe are not always found in the so-called trade-wind belts, notably exceptions occurring in South America on both sides of the Andes between Peru and Patagonia; also in central Asia east of the Caspian Sea and in the southwest of the United States. Moreover, it is believed that the expression "trade winds" commonly refers to winds over a water, rather than a land surface. The regularity of the trades is disturbed by land areas and while the general direction of these winds is not greatly changed when passing from sea to land the velocity and steadiness are not the same.—*Editor.*

THE CLIMATIC PROVINCES OF THE EARTH

(After Köppen, Petermanns Mitt, 1918, Pl. 10)

Scale 1:87 000 000

The Geographical Review, Vol. VIII, No. 3, 1919, Pl. II

FIG. 1.—Köppen's map of the climatic provinces of the earth. (Courtesy of the *Geographical Review*, published by the American Geographical Society, Broadway at 156th Street, New York.) NOTE.—The numbers 8 and 9 in the legend for "D-sub-Arctic climates" should be interchanged.

98186. (To face page 69.)

CRITERIA FOR DETERMINATION OF REGIONS.

With this general statement, we may now take up the actual criteria which are used to determine the boundaries of the different regions.

I. POLAR REGIONS.

The regions of cold are subdivided into perpetual-frost climates (11), and tundra climates (10). The perpetual-frost climate is one where snow and ice is a permanent condition. The isotherm of 0° [4] for the warmest month is used here, and sets off the ice sheets of Greenland and Antarctica, and the snow-capped summits of mountains.

In choosing the criteria for the tundra boundary, it should be remembered that the decisive temperature factor for organic life, including man, consists in the absence of a sufficiently cold season in low latitudes and of a sufficiently warm season at high latitudes. Neither extreme summer heat nor extreme winter cold has a similarly clear influence. Against these extremes the plant world protects itself by a period of rest. For this reason the isotherm of 10° for the warmest month was chosen as the tundra boundary, which limits approximately the poleward growth of forests.

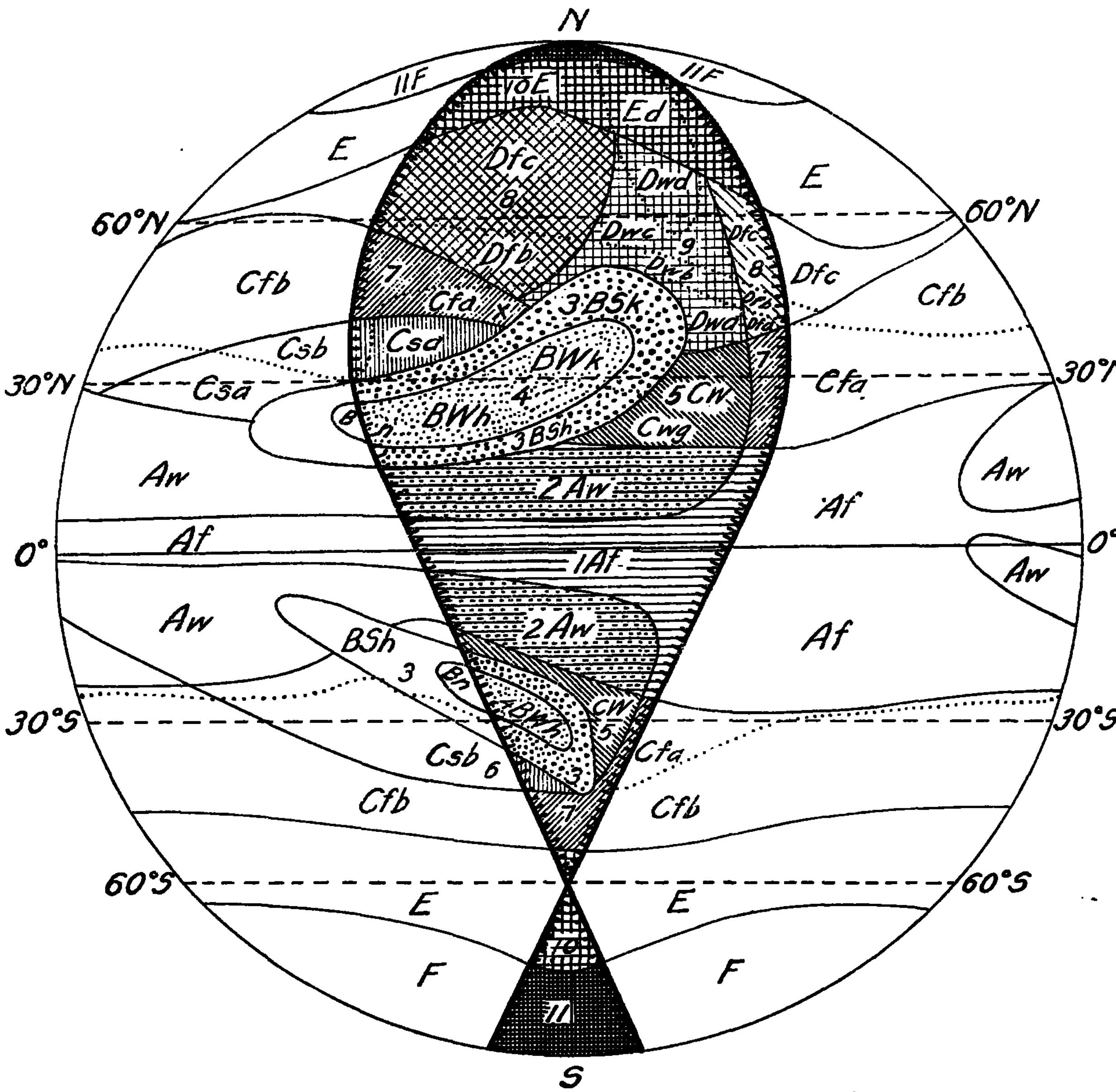

FIG. 2.—Köppen's ideal continent.

II. ARID REGIONS.

The essential feature in these regions is the absence of surface run-off. Everywhere evaporation is greater than precipitation, and no streams may originate. Since evaporation increases with higher temperatures, it is obvious that a given amount of rainfall in a region with a mean annual temperature of 20° might be completely evaporated, whereas in a region with a mean annual temperature of 15° this same amount of rainfall might provide abundant run-off. Therefore, no fixed amount of rainfall can be taken as the arid boundary.

Furthermore, if rainfall comes altogether or largely in the colder months, less will be evaporated than if it comes in summer, so that further allowance must be made for

[4] Temperatures given in centigrade; rainfall in centimeters.

the season in which the rain comes. Köppen has worked out the following table for this, using the desert boundary in every case, as twice that of the steppe:

Temperature.	25° C.	25–20° C.	20–15° C.	15–10° C.	10–5° C.	5° C.
Desert boundary (cm.)	32	29	26	23	20	16
Steppe boundary (cm.)	64	58	52	46	40	32

The season in which the rain falls is considered, when there is a pronounced summer rainfall, by taking 30 per cent higher than the figure in the tables; and when there is a pronounced winter rainfall, by taking 30 per cent lower. Thus the boundaries of the desert and steppe are determined by a combination of rainfall, temperature, and seasonal rainfall distribution. The desert is region 4 on the map; the steppe is No. 3.

III.—HUMID REGIONS.

A. The Tropics.—Within the large area of forest or rainy climates, we find a great variety of conditions, according to (1) temperature, which decreases with increasing latitude or altitude; (2) according to annual ranges, which increase with greater continentality; and (3) with the occurrence of dry seasons. In the vegetable world this variety is expressed by periods of rest, sometimes due to cold, sometimes to drought.

As was mentioned above, summer heat is not as important a factor on the boundary of the Tropics, as is a season of sufficient coolness. For this reason Köppen chooses as his boundary of the tropical rainy climates, the isotherm of 18° for the coldest month. The regions thus defined are divided into types (1), where there is a constant rainfall and (2) types where there are one or two marked dry seasons in the year. In the former, the vegetation is the usual tropical rain forest, but the latter is generally characterized by a savanna or grass land. In certain regions of Type 2, however, we find a growth of tropical vegetation in spite of a sharply defined dry season. This is produced because the rainfall in the wet season gives sufficient moisture to last throughout the dry period in the ground. Where the rainfall is more than 20 centimeters, as on the Malabar coast the dry season may last as much as four months. Such conditions occur especially in monsoon regions. The rain forest may also grow along river valleys, as along the southern tributaries of the Amazon, where the moisture is supplied in abundance from the savanna uplands into the canyonlike valleys.

Grasslands, also, may appear in a constantly rainy climate where the inhabitants are accustomed to burning the savannas bordering the region, as in portions of Africa.

In this group, it is unimportant to distinguish the season in which the rain falls, since the yearly ranges of temperatures are very small. In fact, the seasons themselves are determined by the rains and not by temperature, as in the extra-tropical regions.

Since the deserts are interrupted on the eastern sides of the continents, as mentioned above, the periodically dry savanna climates may merge directly with the warm temperate regions. But whatever the adjoining region may be, the boundary of the Tropics is always taken as the isotherm of 18° for the coldest month.

2. *Warm temperate group.*—The arrangement in the Temperate Zone is complicated because in this case it makes an essential difference whether the rainy season comes in the cold or in the warm part of the year. Therefore, there are three warm temperate climates: Rainy summers (5); rainy winters (6); constantly moist (7).

Climate 5 is a continental type with a summer maximum of rainfall. It is bounded toward the Equator by the isotherm of 18° for the coldest month. It is distinguished from 6 and 7 by the rainy season: the rainiest month of the warm season brings 10 times as much rainfall as the driest month of the cold season.

Climate 6 is the well-known Mediterranean climate, sometimes known as the subtropical type, which is so well developed on the west coasts of the continents in the Horse Latitudes. As its name inplies, the best example is in the Mediterranean countries but it also reappears in characteristic form in California, Chile, Cape Town, and southwest Australia. This is a marine type with winter rainfall. Since evaporation is less than in Type 5; owing to the low-sun character of its rainy season, the region includes only those areas where the rainiest month of the cold season brings three times as much rain as the driest month of the warm season.

Climate 7 is a characteristic east coast type, in which there is sufficient rain in all seasons, so that it is not classed in either of the foregoing.

3. *Sub-Arctic group.*—The sub-Arctic climates are separated from the warm temperate climates on the basis of a regular annual snow covering for a period of several weeks. This snow blanket is a very important factor in vegetation. The isotherm which coincides with the southern boundary of such a snow blanket in regions of sufficient humidity is that of −2° for the coldest month. The term sub-Arctic is permissible for this group, since in southern South America—the only southern hemisphere continent which lies near enough to the pole to reach such climates—the isotherm of 10° for the warmest month (the equatorial margin of the tundra) lies farther from the pole than the isotherm of −2° for the coldest month. This is due to the marine type of the southern Temperate Zone, with its resulting small ranges, and is illustrated by the temperatures at Cape Horn (January, 9. 1° C.; July, 0.1).

Climate 8 is one in which rain or snow occurs in all months and is similar in this respect to climate 7 of the previous group. It is distinguished from 7 only on the basis of a regular snow covering in winter.

Climate 9 is an extreme continental type, occurring only in central Siberia. Here the region with a distinct summer maximum rainfall, and with rainless winters, is set off as distinct from Type 8. These clear, winter skies give us the conditions for the maximum of winter radiation, just as the hot deserts give us the maximum of high-sun insolation.

CLIMATIC SYMBOLS.

In addition to his division of the earth into the foregoing regions, Köppen enriches his map with a series of climatic symbols, indicating the variations and special developments which are found within the more general regions. These symbols need no discussion, but are translated in the following table:

(*a*) Mean temperature of the warmest month over 22°.

(*b*) Mean temperature of the warmest month under 22°, at least four months over 10°.

(*c*) Only one to four months over 10°, coldest month over −36°.

(*d*) The same, but coldest month under −36°.

(*f*) Constantly moist (sufficient rain or snow in all months).

(*g*) Ganges type of annual temperature range with maximum before the turn of the sun and the summer rainy season.

(*h*) Hot, annual temperature above 18°.
(*i*) Isothermal, difference between extreme months less than 5°.
(*k*) Cold winter, annual temperature below 18°, warmest month above 18°.
(*k'*) The same, excepting warmest month below 18°.
(*m*) Monsoon rains, primeval forest in spite of one dry period.
(*n*) Frequent fogs.
(*n'*) Infrequent fogs, but high humidity accompanied by lack of rainfall, and relatively cool (summer below 24°).
(*p*) The same, with a higher temperature (summer above 28°).
(*p'*) The same, but with summer temperatures 24° to 28°.
(*s*) Dry season in summer of that hemisphere.
(*w*) Dry season in winter of that hemisphere.
(*s' w'*) The same, but rainy season delayed after autumn.
(*s'' w''*) The same, but rainy season overlapping with small dry season introduced.
(*u*) Sudan temperature course, coldest month after turn of the sun.
(*v*) Cape Verde course of temperature, warmest month in autumn.
(*x*) Transition type with early summer rain.
(*x'*) The same with infrequent but intense rain at all times of the year.

L. F. RICHARDSON ON WEATHER PREDICTION BY NUMERICAL PROCESS.

By EDGAR W. WOOLARD.

[Weather Bureau, Washington, D. C., March 15, 1922.]

Weather forecasting as conducted by the chief meteorological services of the world for many years past is completely empirical. Yet it can not be doubted that the processes of weather are simply examples of the operation of ordinary physical laws, although special methods may be required for the treatment of the special problems involved. The ultimate object of all meteorological work is to lead up to an insight into the physical processes which effect changes in weather—all our forecasting is the anticipation of these changes. The method of forecasting by empirical rules and past experience is simply a stage in the classification of the physical processes; it leads, as we know, to excellent results in the hands of the experienced, but its capacity is limited, and the limit is very soon reached. To carry it further, or to make out the true inwardness of its application in special cases, we must depend upon our knowledge of the dynamics and physics of the atmosphere.

In the present position of meteorological science, there are two extremes of opinion, both of which ought to be, and undoubtedly are by most meteorologists, avoided: Either to think the penetration into the secrets of the subject to be so difficult that we must be content to forego the attempt and deal with what we have; or to think it so easy that only observations are required, and the training of our brains of no account. As a matter of fact, brains without observations are certainly of no avail at all in any problem dealing with Nature; and observations, however numerous and widely distributed, will not exonerate us from the use of highly trained intelligence.[1]

Meteorology becomes exact only to the extent that it develops into a physics of the atmosphere. The ancients had a not inconsiderable knowledge of both meteorological facts and certain branches of physics, but no one dared to combine this knowledge in order to explain, for example, the monsoon winds. The growth of meteorological and of physical knowledge during and after the Renaissance prepared the way for some investigating spirit to perceive, sooner or later, the relationship between meteorological phenomena and physical laws; this relationship between the two sciences first came to be recognized, and the first step taken toward the development of a physics of the atmosphere, in the work of Halley and of Hadley, just following the great revolution in astronomy. However, by one stroke astronomy became an exact science, while meteorology took only a step in that direction. The transformation of meteorology into an exact science necessarily, from the transcendent complexity of the problems involved, called, and still calls, for extensive further development of both theoretical physics and observational meteorology.

Parallel with the subsequent steady progress of experimental and theoretical physics and of pure mathematics, was a growth of knowledge of climatology and descriptive meteorology. The combination of meteorological and physical facts has resulted in many excellent studies of theoretical meteorology, particularly since the time of Ferrel's pioneer work on the mechanics of the earth's atmosphere. Such studies are of the utmost importance to the practical problem of forecasting, since they help toward a better understanding of the phenomena of the atmosphere. Furthermore, in addition to having their scientific importance and interest, they bring us nearer the ultimate goal of the possibility of making forecasting a science instead of an art. With complete observations available from an extensive portion of the free air, the problem is to apply the equations of mathematical physics to the actually existing atmospheric conditions, and to compute the conditions that will follow. An objection usually urged against this idea is, "How can this be of any use? The calculations must require a preposterously long time. Under the most favorable conditions it will take the learned gentlemen perhaps three months to calculate the weather that Nature will bring about in three hours. What satisfaction is there in being able to calculate to-morrow's weather if it takes us a year to do it?" However, in the words of Bjerknes,[2] "If only the calculation shall agree with the facts, the scientific victory will be won. Meteorology would then have become an exact science, a true physics of the atmosphere. When that point is reached, *then* the practical results will soon develop. It may require years to bore a tunnel through a mountain. Many a laborer may not live to see the cut finished. Nevertheless this will not prevent later comers from riding through the tunnel at express-train speed."

Contemporary research in this field is being carried on largely by V. Bjerknes, of Norway, and L. F. Richardson, of England. It is to the latter that we owe the remarkable work now before us, *Weather Prediction by Numerical Process.*[3] Previous investigations have considered but one or two phases of the general problem—usually the purely dynamical—and have frequently been limited to more or less idealized conditions. Mr. Richardson, however, has dared to begin the discussion of the motions and phenomena of the *actual* atmosphere under the combined influences of *all* the principal factors, including radiation and absorption, evaporation and condensation, eddy motions or turbulence in the lower atmosphere, etc., gathered into one set of systematic mathematical equations, and to attempt to utilize this

[1] *Cf.* Sir Napier Shaw, "The Outlook of Meteorological Science," MO. WEATHER REV., 48, 34, 1920; *Quar. Jour. Roy. Met. Soc.*, 45, 95, 1919.

[2] V. Bjerknes, "Meteorology as an Exact Science," MO. WEATHER REV., 42, 14, 1914.

[3] Lewis F. Richardson. *Weather Prediction by Numerical Process*, Cambridge Press 1922. 4to, xii, 236 pp. The manuscript was completed in 1916, but was revised, and a numerical example worked out, in France during intervals of transporting wounded, 1916-1918. Upon being sent to the rear in 1917 the working copy was lost, to be rediscovered some months later under a heap of coal. It was again revised in 1921.